SPIN ECHO DELAY LINE: A MEMORY DEVICE BASED ON NUCLEAR MAGNETIC RESONANCE

(Preliminary Report)

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I Introduction

Exploratory work has been done at the Control Systems Laboratory since April 1952, on the practical exploitation of the memory feature inherent in the spin echo\(^{(1)}\) phenomenon. Using relatively crude equipment, it has proved feasible to store some thirty pulses for times up to 5 milliseconds. The signals stored were radar range markers of 1 microsecond duration and spaced at 10 microsecond intervals. It seems probable that at least as many marks could be stored if written in at 1 microsecond intervals, and, further, that storage times of more than a second are feasible. One of the arrangements to be described here will be seen to provide a delay-line type of storage possessing the unusual feature of asynchronous operation.

II The Spin Echo Effect

No attempt will be made to discuss here the theory of the spin echo phenomena\(^{(1)}\). In general, the basic experiment involves the application of a pair of pulses of radio frequency power to a sample of nuclear spins which has been placed in a fixed magnetic field, \(H_0\). If the radio frequency satisfies the Larmor resonant condition for the sample nuclei, \(\omega_0 = \gamma H_0\), \((\gamma\) is the nuclear gyromagnetic ratio which is of such a magnitude that \(\frac{\omega_0}{2\pi} = 30\) mc for protons in 7000 gauss) then certain

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\(^{(1)}\) E.L. Hahn, Phys. Rev. 80, 580 (1950).
transient nuclear induction signals ("Bloch decays") are observed following each pulse and, further, there arises a spontaneous radio frequency signal (the "spin echo") from the sample at a time equal to twice the separation ($\tau$) of the pulses (Fig. 1). As $\tau$ is increased the amplitude of the echo usually decreases exponentially with a time constant $T_2$ which is inversely related to the linewidth of the resonance, $\Delta H$; $T_2 = \frac{K}{\gamma \Delta H}$ (where $K$ depends on the lineshape). The echo width is described by a time $T_2^*$ which is the inverse of the magnet inhomogeneity prevailing over the sample area. ($T_2^* = \frac{K^*}{\gamma \Delta H_0}$). Thus, to get a sharp spin echo of good time resolution, an inhomogeneous magnetic field is required. $T_2^*$ is also the time constant of the Bloch decays for an inhomogeneity distribution of Lorentzian shape (if $T_2^* \gg T_2$).

If a third pulse of rf power is applied at some later time, $T_3$ then a Bloch decay and a "stimulated echo" occur (Fig. 1). The stimulated echo appears at a time $T + T_1$ and, under the proper conditions, decays exponentially as $T$ increases with the time constant $T_1$, the spin-lattice relaxation time. Physically $T_2$ must be $\leq T_1$ and for various typical liquid and solid
materials \( T_1 \) and \( T_2 \) range from microseconds to seconds. In addition to producing the stimulated echo, the third pulse acts as a mirror for all that has gone before; producing echoes in turn of the 1st and 2nd rf pulses and of the spin echo itself.

**III Applications of Memory Aspects**

Certain memory-like characteristics are apparent in the spin echo phenomena. The time \( \tau \) is remembered by the spin ensemble and is reported by the echo and, upon demand, again by the stimulated echo. Further, the phenomenological equations describing the echo effects \(^1\) show that (neglecting diffusion effects) the Bloch decays maintain the phase of the driving rf after it has been turned off. The multiplicity of echoes also have predictable phase relationships.

The experiment may be performed with a pulsed phase-incoherent rf source, in which case there is no coherence between the Bloch decays and the echoes, but the decays still maintain the phase of their respective pulses. If a phase shift of \( \alpha \) exists between the 1st and 2nd rf pulses, the primary echo occurs with a resultant phase shifted \( \alpha + \tau / 2 \) from that of the 2nd pulse \(^1\). The phase memory of the Bloch decays could be used as an echo box operating at intermediate frequency in an M.T.I. radar, if a stable microwave local oscillator were available. A Bloch decay can be made to "ring" for many milliseconds or even seconds if necessary.
The investigation carried out at C.S.L. has thus far been concerned with the memory qualities of the echoes. Our experiments have involved the substitution of more or less complex arrays of information pulses for one or more of the usual rf pulses 1, 2 or 3 (Figs. 1 and 2). The data pulses are "written in" at a much lower rf level than the ordinary "stimulating" pulses, but the total energy in the assembly of data marks is usually of the same order as that in one of the large pulses. The level of the data marks is, in fact, sufficiently low that spin echoes arising among them are of negligible amplitude.

It is a remarkable feature of the experiments that within certain experimental limits echoes appear which faithfully reproduce the sequence and relative amplitudes of the data marks. Three simple cases may be considered, all of which involve the substitution of multiple marks for some one of the normal rf pulses. Case I (Fig. 2) shows schematically the situation arising if the data marks are substituted for the first pulse. In this case the spin echo will present a reflected reproduction of the write-in with the time sequence of the data inverted. Similarly the stimulated echo will be in reverse sequence, but the "echo of the echo" at 2T - 2\(\tau\) is in the original sequence. If \(\tau\) is regarded as the write-in time and T the memory time (or time until the stored data is requested) then the access time of the proper-sequence data at 2T - 2\(\tau\) is an inconveniently long T - 2\(\tau\). If an inverted order of the read
CASE I.

![Diagram of CASE I.]

CASE II.

![Diagram of CASE II.]

CASE III.

![Diagram of CASE III.]

Figure 2.

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out produces no difficulties then the stimulated echo is more attractive with its relatively short access time, $\tau$.

Skipping case II for the moment we see that in case III, which appears to be of little immediate practical interest, we can set up a time $\tau$ in the normal manner and then observe a multiple stimulated echo following a multiple stimulating pulse. The order of these stimulated echoes is not inverted.

In arrangement II, the data marks are inserted in place of pulse #2 and give rise to an echo of complex appearance. The stimulated echo, however, reproduces the write-in in proper time sequence. It is this arrangement, II, which seems the most interesting from the standpoint of data storage. The operation in this case is analogous to that of a conventional delay line. The data is read in serially in time and, after a controllable delay, is read out with the same sequence and spacings. There are certain features of the device which differ from those of the conventional delay line. The number of pulses storable, for example, is at present sharply limited to about 30 (see section VI). This is not the number of bits stored since multi-level pips may still be distinguished at this packing number and the number does not include the number of gaps or nulls which may occur. An advantageous feature is that the delay or memory time is variable over an extremely wide range from microseconds to seconds with the read-out access time guaranteed to be independent of any variation of the delay time. The device is thus self-synchronizing in the sense that, for example, the stored data from a radar having an unstable pulse repetition frequency would
superimpose in range with the information contained in subsequent p.r.f. intervals.

IV Experimental Arrangements

The equipment (Fig. 3D) used in the C.S.L. experiments includes an electromagnet equipped with conically tapered pole pieces such that there exists a field inhomogeneity of some 100 gauss over a sample of about 1 cm² cross section. The inhomogeneity limits the echoes to a width of a few microseconds at half maximum.

An rf bridge of 1 mc bandwidth has been constructed - a device essential for the observation of echoes arising from microsecond pulses. Exact balance of the bridge is not critical since its only purpose is the prevention of extreme saturation of the receiver. Bridge coils having an artificially reduced Q are used in a symmetrical circuit (Fig. 3A) which permits balance over a range of frequencies.

It may be shown that the signal obtained from the spin sample is proportional to the volume of the sample. Furthermore, for a constant bridge bandwidth and a given $H_1$, the power dissipated in the bridge circuit is also proportional to the size of the sample. It was felt that, for the present investigation, simplicity of equipment was more important than a good signal-to-noise ratio. Therefore, small samples ($\sim 0.25$ ml) were used. Improved signal-to-noise ratio may be obtained through the use of larger samples and by the crossed coil technique(2) which eliminates

(2) F. Bloch, W.W. Hansen, and M. Packard, Phys. Rev. 70, 474 (1946)
Figure 3A
Bridge Circuit

NOTE:
The three bridge coils each tune 30 MHz with a capacity of 5 μF.
Figure 3B

Block diagram of modulator-oscillator unit
Figure 3C
Block diagram of RF Amplifier
the dissipation of signal power in the auxiliary coil and in the transmitter which is matched into the bridge for reasons of power economy.

The first experiments at C.S.L. made use of the receiving tube pulsed oscillator (Fig. 3B). A blocking oscillator of adjustable pulse length is provided to drive the rf oscillator to saturation on pulse signals. A separate input for data signals provides adjustable amplitude pulses determined by the output level settings on the various pulse and marker generators which may be fed in through a mixer circuit (Fig. 3C). It soon became apparent that the oscillator power was inadequate and an amplifier (Fig. 3D) with a peak output of several kilowatts corresponding to an rf $H_1$ of perhaps 20 gauss was added. The upper power limit was imposed by arcing at the high impedance sample coils.

Hahn has shown\(^1\) that for the echo signal amplitude to be independent of the field homogeneity $\Delta H_0$, the rf power must be such that $H_1$ "covers the line"; that is $H_1 \geq \Delta H_0$. Thus one microsecond resolution, which implies $\Delta H_0 \approx 100$ gauss, would require the production of more than 100 gauss rf in the sample coil for optimum signal-to-noise ratio. Work has started on radio frequency and pulse equipment which, it is hoped, will meet this specification. Increased efficiency will be obtained through the use of a common coil for the rf tank circuit and the nuclear resonance sample. This minimizes the energy storage in
the rf system and consequently reduces the dissipation required to achieve a given bandwidth.

The block diagram (Fig. 3) shows the interconnection of equipment for obtaining the data shown in Fig. 4, frames C, E, and F. The Teletronics instruments each provide simultaneously available range markers, sliding pulse and fixed pulse which when connected with the other instruments through a mixer, permit many combinations of data and pulses. Adjustments are made to provide data signals with roughly one-tenth the power of the pulse signals. An APS-10 radar i.f. strip amplifies and detects the nuclear resonance signal which is then displayed on the oscilloscope.

V Preliminary Experimental Results

Figure 4 shows oscillograph photos of the pulse and stored data for various arrangements. The exposures were made over several repetitions of the pulse array. The large rf pulses and the smaller data markers all appear of the same amplitude due to saturation of the i.f. amplifier. The data marks were one $\mu$-second long and separated by ten $\mu$-seconds.

Frames (a) and (b) show the "delay line" arrangement, case II (cf. Fig. 2), for different delay times and data configurations. The echo in frame (a) shows the non-reproduction of the write-in shape which is characteristic of case II. Frame (b) more closely approximates practical memory operation with delay time much larger than the write-in (and access) time.
a. **CASE II**  
*5 DATA MARKS*  
*600 μSEC SWEEP*

b. **CASE II**  
*11 DATA MARKS*  
*1 MSEC SWEEP*

c. **CASE I**  
*MULTILEVEL DATA*  
*0.4 MSEC SWEEP*

d. **CASE III**  
*5 DATA MARKS*  
*600 μSEC SWEEP*

e. **MAGNIFICATION OF ECHO IN C.**

f. **MAGNIFICATION OF STIMULATED ECHO AND "ECHO OF ECHO" IN C.**

**Figure 4**
Frames (c), (e), and (f), show the array of Case I. Multi-level data marks were used to show the inverted time sequence characteristic of all the echoes except the "echo of the echo". The rf level may be adjusted to make this latter signal larger than the stimulated echo of frames (c) and (f). Frames (e) and (f) show the faithful reproduction and good time resolution in the echo and stimulated echo.

Frame (d) shows the pattern observed for case III with the production of a multiple stimulated echo, given an established time $T$ and the multiple data marks.

VI Limitation of Information Capacity

The major defect of the spin echo delay line appears to be a limited information capacity. The present crude experiments indicate that the maximum capacity may be of the order of 100 bits. The experimental evidence for such an estimate is as follows: If one uses pulse arrangement II, for example, (cases I and III would serve equally well) and writes in some dozen or so marker pulses, then it is observed that, if the rf amplitude of these data pulses is increased, eventually the reproduction of the stored data by the stimulated echo becomes imperfect. The imperfection is generally a decrease in the amplitude of the center members of the sequences of stored pulses so that a saddle-like envelope appears.
Similarly, if one starts from a satisfactory storage pattern and increases the number of pulses written in, then the same drooping or saddle effect is observed. In some cases the diminished members of the stored array are reduced completely into noise. If such a number of pulses has been written in that the saddle effect has appeared, then it is possible to reduce the distortion by lowering the rf amplitude of the markers written in. The limitation appears to be one of the total rf energy contained in the information array. It seems clear that the question of the maximum number of pulses ultimately storable becomes one of the signal to noise ratio attainable with the equipment.

The physical phenomenon behind the drooping is probably associated with the introduction of sufficient rf energy into the spin system to carry the experiment beyond the region of linearity. The fact that the limitation seems to be upon the total rf energy that can be contained in the information written in means that the presence of spaces or non-existence of pulses does not (within certain limits) advance the system towards non-linearity. Therefore the number of resolvable pulses which can be stored is a lower limit to the information capacity. To this may be added a reasonable number of spaces for a more realistic estimate of the digital storage capacity.

VII Present Status and Future Plans

We intend to continue the attempt to store more pulses by improving the signal to noise ratio attainable with the equip-
ment and also to increase the time resolution of the stored pulses. The latter effort will require rf magnetic fields of several hundred gauss to fully utilize the bandwidth of the equipment. Theoretical considerations of the cause of the saddle effect will be continued.

Certain preliminary inquiries have been made into the question of the existence of a dynamic range of integration inherent in the effects. The question is one of how succeeding echoes are affected by the presence of echoes from previous data superimposed upon the rf pulses. We hope that it may prove feasible to use the device for delay line type of integration of analog data.

Conversations with Drs. Bloch, Hahn, and Proctor of Stanford University have revealed that a similar investigation is being pursued there (3). They have been particularly interested in a theoretical and experimental consideration of the fidelity with which the shape of a stored pulse is reproduced. Further, they have sought compounds suitable for data storage over periods as long as is feasible. The long-time memory problem is more complicated than a search for compounds possessing suitable values of $T_1$ and $T_2$. Hahn has shown (1) that echo signals are much reduced as a result of diffusion of the processing nuclei from a region of one local field to that of another. The combination of long storage times and large gradients in $H_0$ results in stringent limitation of acceptable

(3) Progress Reports, Contract Monr 225 (Ol4), Stanford University
diffusion rates or of the actual diffusion distances. After considerable research the Stanford group have recently found that in certain oil suspensions $T_1$, $T_2$ and the maximum diffusion range are all quite suitable for data storage times of the order of a second.